

Link Characterization for Deep-Space Optical Communications

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ABSTRACT. — We report the performance of candidate deep-space optical communication systems that would use a single optical ground station in conjunction with various space terminals. We considered three potential diameters of ground receive terminals (4 m, 8 m, and 12 m) and three potential ground transmit powers (1 kW, 5 kW, and 10 kW). Combinations of ground receive terminals, ground transmit terminals, and spacecraft terminals were assessed for data rate and data volume return, both uplink and downlink, and for uplink irradiance needed to enable downlink pointing. System performance was evaluated in the context of a set of 12 design reference missions described in a companion article in this volume. Link performance was evaluated using the Strategic Optical Link Tool, assuming clear weather conditions with conservative desert daytime turbulence. We compared the link performance achievable under our assumptions to the anticipated requirements associated with the design reference missions.

I. Introduction

In this article, we report the forecasted system performance of optical communication links using a single optical ground station and various space terminals. We adopted the article by Breidenthal and Abraham [1] as the reference for a set of potential missions that might eventually use optical communication. Combinations of ground receive terminals, ground transmit terminals, and spacecraft terminals were assessed for data rate and volume (both uplink and downlink), and for uplink irradiance needed to enable downlink pointing.

Link performance was evaluated using the Strategic Optical Link Tool (SOLT).¹ The SOLT was built off the Deep Space Optical Link (DeSOL) software,² which was designed to gener-

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¹ H. Xie, J. Wu, B. Moision, and S. Piazzolla, "Strategic Optical Link Tool," presentation for PSE Annual Review, October 2012.

² S. Piazzolla, "Deep Space Optical Link (DeSOL) Software," JPL Optical Communications Group, 2008.

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ate link budgets with sufficient accuracy for mission design. SOLT develops the link budget by deriving the received signal and noise power and mapping them to achievable data rates. We assumed pulse-position modulation (PPM) of the laser with direct detection for the analysis in this article. The set of 12 design reference missions (DRMs) [1] encompasses a range of orbit types, terminal sizes, and positions in the solar system to reveal the chief system performance variables of an optical ground segment. They may be used to enable assessments of the ability of alternative systems to meet various types of customer needs.

Basic optimistic assessments of raw physical link performance were made assuming clear weather conditions and desert daytime turbulence (zenith $r_0 = 5.5$ cm at 500 nm). We evaluated the average supportable data rates and the cumulative data volume as a function of time for the set of design reference missions.

II. Metrics of Data Acquisition

In this article, we report the data rate and data volume metrics for optical communication. The other data acquisition metrics, such as link availability, continuity, and latency, are reported in a companion article [2].

A. Data Rate

An inherent characteristic of optical links through Earth's atmosphere is that their performance depends on atmospheric transmittance, turbulence, and solar radiance. As a consequence, the supportable data rate in any real data acquisition will vary substantially with actual weather, range, elevation, and Sun–Earth–probe (SEP) angles.

We evaluated the supportable data rate as a function of time for a number of DRMs, subject to an error rate constraint and a number of assumptions about operating conditions. The reference missions, described more extensively in [1], were constructed to resemble a number of potential future missions that are currently within the set of options under consideration by NASA.

To determine the supportable data rate for each DRM, we evaluated the link situation at fixed intervals of time ranging from 5 to 30 min, and covering relevant periods of interest. For each moment evaluated, we optimized the link parameters, e.g., field of view (FOV), PPM order, code rate, and slot width, for the link situation using the methods described in Section V.A. Link budget calculation produces a time series of supportable data rate. In most cases, the optimum data rate changed many times during a pass, as illustrated in Figure 1. For the purposes of ground segment evaluation, we reduced these variations to an average data rate during the pass, by calculating the single-pass data volume, and then dividing by the pass duration. The forecasted instantaneous data rates typically vary by a factor of 2 or more from the average, except for the all-night passes (e.g., SEP greater than 90 deg).

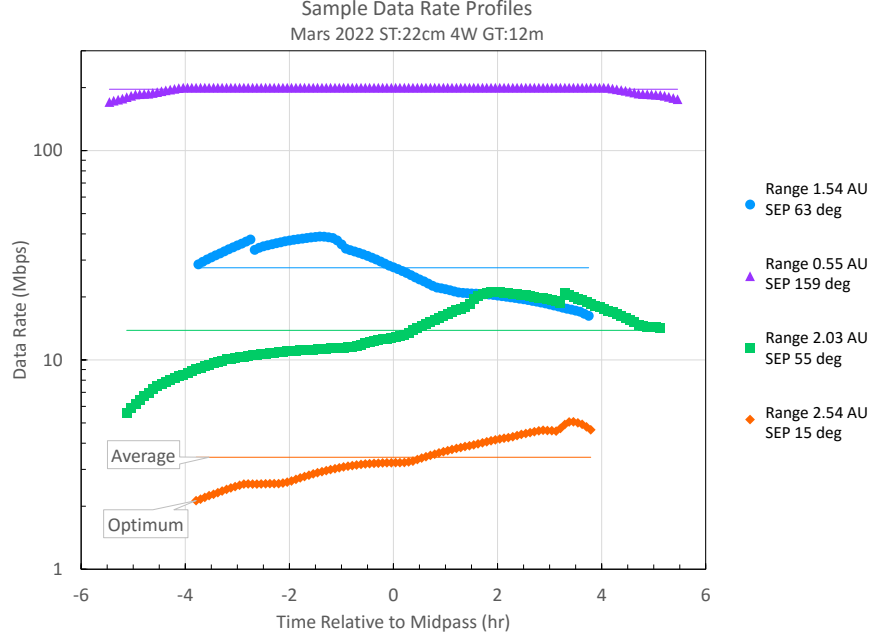


Figure 1. Samples of the optimized optical data rate profiles during a pass.

B. Data Volume

We calculated single-pass data volume by taking the average of adjacent data rates for each time interval evaluated during the pass, and then multiplying by the interval. The average of adjacent rates minimizes bias arising from evaluating at regular intervals, considering the possibility that the precise time of data rate change could occur anywhere in the interval. We also calculated a cumulative data volume as a function of time for each mission, by summing the individual pass data volumes. The cumulative data volume is presented in two forms: ideal and realistic. For the ideal case, which is considered in this article, we assumed use of all available passes for a single receiving site, cloud-free line of sight (i.e., there are no clouds of any sort, including subvisual cirrus clouds), and no losses due to weather. The impacts on data volume due to weather are discussed in [1] and [2].

III. Optical Terminal Characteristics

A. Ground Receive Terminal Characteristics

We examined the system performance resulting from three sizes of ground receive optical terminals: 11.8 m (nominally 12 m), 8 m, and 4 m. For all of the terminals, we assumed that they possess characteristics as listed in Table 1. The downlink budget calculation assumes a single detector for compatibility with the current software. In practical systems, detector arrays are used to increase the peak data rate by reducing blocking loss. For the link budgets presented in this article, we treat blocking loss as a constant rate attenuation, i.e., 0.2 dB. Our future software will incorporate detector arrays for link characterization.

Table 1. Ground receive terminal characteristics.

Characteristic	Value
Diameter	11.8 m, 8 m, 4 m
Wavelength	1550 nm
Filter Bandwidth	0.17 nm
Optical Loss	4.1 dB
Cleanliness Level	1000
Number of Detectors	Single
Blocking Loss	0.2 dB
Detector DE	50%
Minimum Slot Width	500 ps
Detector Dark Rate	225 kcounts/s
Detector Jitter	100 ps
Field of View	Adjustable

B. Ground Transmit Terminal Characteristics

For deep-space missions, we examined the system performance resulting from three transmit powers of ground optical terminals: 1 kW, 5 kW, and 10 kW. For the Moon reference missions, we used 10 W, 50 W, and 100 W. For all of the terminals, we assumed an aperture carrying multiple small beams sized to match the Fried parameter of atmospheric turbulence; for higher power, larger numbers of beams were used consistent with the uplink systems described in [3,4,5,6]. For all of the ground transmit terminals, we assumed that they possess characteristics as listed in Table 2.

Table 2. Ground transmit terminal characteristics.

Characteristic	Value
Beam Diameter	3 cm at aperture plane
Number of Beams	9 to 18
Beam Angular Dispersion	40 μ rad
Average Transmit Power	10; 50; 100; 1000; 5000; 10,000 W
Peak/Average Power Ratio	160 maximum
Wavelength	1030 nm
Limits on Data Rate	Existing uplink for DSOC: a few kbps Near-term: ≥ 292 kbps Long-term: ≥ 25 Mbps
Optical Loss	3 dB

We are aware of near-term limits on the uplink data rate to a few kbps, and a limitation of the Deep Space Optical Communications (DSOC) space terminal command rate to 292 kbps. However, we expect that these limits will be raised in the long term to levels that could permit power-limited performance of the uplink. The wavelength of 1030 nm was an early value quoted by A. Biswas,³ since changed to 1064–1070 nm. The IPN Technology Program is currently using 1030–1080 nm as the possible range.

³ A. Biswas, “DSOC,” presentation for DSOC Technology Day, April 2014.

C. Space Terminal Characteristics

We examined the system performance resulting from five sizes of optical space terminals, ranging from 2 cm to 50 cm in diameter, and having transmitter powers ranging from 2 mW to 20 W. We assumed other terminal characteristics consistent with the DSOC terminal described in [7]. These characteristics are summarized in Table 3.

Table 3. Spacecraft terminal characteristics.

Characteristic	Very Small	Small	Medium	Large	Large
Aperture Diameter, cm	2	5	22	30	50
Transmit Power, Average, W	0.002	1	4	10	20
Uplink Wavelength, nm	1030	1030	1030	1030	1030
Number of Uplink Detectors	Single	Single	Single	Single	Single
Uplink Detection Mode	Photon Counting	Photon Counting	Photon Counting	Photon Counting	Photon Counting
Uplink Detection Blocking Time	500 ns	500 ns	500 ns	500 ns	500 ns
Minimum Slot Width	1 ns	1 ns	1 ns	1 ns	1 ns
Downlink Wavelength, nm	1550	1550	1550	1550	1550
Peak/Average Power Ratio	160	160	160	160	160
Optical Loss, dB	3	3	3	3	3
Pointing Loss 99.7 percentile, dB	1.46	1.46	1.46	1.46	1.46
Minimum Beacon Irradiance, pW/m^2	4	4	4	4	4

We assumed a single detector for both uplink and downlink in link budget calculation. Actual spacecraft would use at least a 2×2 array for acquisition and pointing. Assumption of a single detector did not introduce significant blocking losses except in the case of the Deep Space Observatory–Nighttime DRM. For this one case, the rate was a constant at the assumed uplink data rate limit with or without an arrayed detector.

The DSOC terminal has a downlink data rate limit of 267 Mbps and an uplink data rate limit of 292 kbps. It is unclear whether all future terminals will have the same limits, which arise for a number of reasons. The SOLT software used for the calculations in this article only evaluated the limit imposed by minimum slot width, which we assumed to be 0.5 ns and 1 ns for downlink and uplink, respectively. If the uplink data detector is part of the tracking detector (as is in the current DSOC concept), then there is also a maximum data rate due to detector recovery time blocking losses. We assumed the recovery time to be 500 ns, a Technology Readiness Level (TRL)–3 capability at present and reasonable to assume use after 2025 under current development plans. With the signal spread across a 2×2 pixel window, a few Mbps can be achieved before blocking losses become prohibitive [17]. The possibility of other limits should also be kept in mind: uplink detector read-out electronics (currently limits to 292 kbps, but could be improved to >100 Mbps), and different types of detectors (also >100 Mbps). In most cases, the current limits would have resulted in uninteresting calculations, always limited regardless of terminal sizes, powers or distance. Therefore, we chose to calculate uplink rate assuming a 200 Mbps limit to reveal what the link capacity might be if improvements can be made.

In all cases, we assumed that the spacecraft's optical beam pointing is sufficient to permit use of the spacecraft aperture at the diffraction limit. Intentionally defocused beams were not considered, though they may be useful in practical system designs to balance terminal footprint against the required data rate. Very small terminals near Earth, in particular, may benefit from intentional defocusing, and may use substantially different pointing architectures. These are beyond the scope of this article.

D. Uplink Beacon Function

We assumed that a beacon-assisted pointing function will be used by the spacecraft terminal. This requires the optical ground segment to provide a minimum uplink irradiance for beacon detection, independent of data rate considerations. We adopted a convention of minimum uplink irradiance of 4 pW/m^2 for the DSOC terminal, and did not scale according to aperture area. This choice has an underlying assumption that the downlink would be constrained to use the full aperture. In this case, the minimum uplink irradiance does not increase with aperture diameter due to the need for finer pointing associated with the larger aperture; the threshold is determined primarily by the detector characteristics, which may vary depending on the terminal design. However, a relaxation of the full-aperture transmission constraint to allow increased receive aperture and subaperture transmission would broaden the downlink beam, reduce pointing requirements, and reduce the required uplink power.

IV. Link Parameter Selection

Optical link budget tools, such as the SOLT, calculate the link budget by deriving the received signal and noise power and mapping them to achievable data rates. The mapping of the signal and noise power to supportable data rate depends on how the signal is modulated and detected. We assumed the PPM of the laser with direct detection for performance analysis in this article. This system has been shown to be practically implementable, and represents the current state-of-the-art system for transmitting at high power efficiencies with optical carriers [8,9]. We will review the link budget calculation for a Poisson PPM channel, and describe the optimization procedure implemented in SOLT for selections of the link parameters that maximize the achievable data rates.

A. Received Signal and Noise Power

The detected signal power [10] at the focal plane of an optical receiver can be represented as

$$P_r = EIRP \cdot G \cdot L_r \cdot L \cdot \eta_\Omega, \quad (1)$$

where $EIRP$ is the effective isotropic radiated power, $G = (\frac{\pi D}{\lambda})^2$ is the receive antenna gain for effective diameter D , $L_r = (\frac{\lambda}{4\pi R})^2$ is the space loss, L includes all the other losses due to atmosphere and system efficiency, and η_Ω is a term we use to characterize the effects of spatial filtering at the receiver. Detailed descriptions of losses and system efficiencies L of the optical link can be found in [11].

The noise power, P_n , is dominated by sky radiance, which can be obtained for the applicable geometry, locations, and atmospheric conditions from the radiative transfer analysis program MODTRAN. Other sources, such as dark current and external planets in FOV, are also included in background noise calculation.

B. Spatial Filtering and Optimal Field of View

Because the background noise is spatially uniform in the focal plane and the signal power is not, one can improve the system performance with a spatial filter, collecting power only over a finite region of the focal plane. We assumed that an iris will be used to adjust the FOV to change the amount of signal and noise photons that get to be collected. This can also be accomplished via signal processing if we replace a single detector with an array.

Reducing the FOV has the effect of filtering out both background noise and signal power. The optimal setting of the spatial filter depends on the incident signal and noise power, as well as the spatial distribution of the signal power. To simplify the procedure of finding the optimal FOV, an analytic approximation to the optimal solution has been derived for varying conditions of incident signal-to-noise ratio [12]. This suboptimal FOV corresponds to always encircling 91 percent of the signal power. It was shown that the maximum loss using this analytic solution is less than 0.4 dB. This analytic solution significantly simplifies the link budget calculation by eliminating the need to iteratively search for the optimal FOV at a given incidental signal-to-noise ratio. We adopted this solution in calculation of the sample link budgets presented in this article.

C. Modulation and Coding

Over a range of target data rates and background noise levels, the most power efficient and practically implementable method to signal at optical frequencies is to use intensity modulation at low duty cycles with photon-counting detectors, which may be modeled as a Poisson channel [13]. Low duty cycles may be efficiently implemented by modulating the data using M -ary PPM. The detector pulse width and receiver bandwidth place a constraint on the minimum supportable slot width. The limitations from the modulation and physical devices set an upper bound for the data rates that are achievable by such a signaling system.

An error-correction code of rate R_{ECC} is utilized to improve power efficiency. The candidate coding for the deep-space optical channel includes Reed–Solomon coded pulse modulation (RSPPM), iteratively decoded serial concatenation of a convolutional code and coded PPM (SCPPM), and low-density parity check (LDPC) codes [13].

The performance of coded modulation can be characterized by its code efficiency relative to the theoretical limit given by the channel capacity. For modern codes such as LDPC and turbo codes, code efficiency is well characterized as a constant over varying conditions. This enables us to model the performance of the codes as a constant in an optical link budget design. The resulting maximum data rate of such a system is

$$R_b = R_{ECC} \cdot \frac{\log_2 M}{M \cdot T_s} \quad \text{bits/s}, \quad (2)$$

where R_{ECC} is the code rate, M is the modulation order, and T_s is the slot width.

D. Capacity and Achievable Data Rate

In developing our link budgets, we sought to choose a triple, $\{R_{ECC}, M, T_s\}$, to maximize the data rate under the constraint that the system fidelity, for example, word error rate, needs to satisfy certain target requirements. The capacity of the channel provides the least upper bound on the achievable data rate with an arbitrarily small probability of error. We say a link can be closed if we transmit information at a data rate R_b that is below the channel capacity C :

$$R_b \leq C. \quad (3)$$

The channel capacity in our signaling system of consideration is a function of the PPM order, slot width, and the received signal and noise flux rates. Except for the noiseless case, evaluation of C_{PPM} requires one to approximate a multidimensional infinite sum or perform a Monte Carlo simulation [8]. This is very time consuming and may obscure the basic relationships between the signal and noise rates and achievable data rates. SOLT adopts various bounds and approximations as developed by Moision and Piazzolla^{4,5}; also see [10], to perform fast evaluations of the capacity functions. This approximation enables SOLT to support large-scale link budget calculation for mission planning, e.g., to perform trade studies on data volumes returned by various ground terminals. In Section V, we briefly describe the SOLT link budget tool and the optimization procedure implemented in SOLT to select link parameters that achieve maximum data rates.

V. Strategic Optical Link Tool (SOLT)

SOLT is a strategic link budget tool developed based on DeSOL software⁶ to facilitate architecture studies for future missions that involve both RF and optical communications. SOLT obtains spacecraft trajectory/geometry data from an orbital trajectory inference engine (OTIE) [14] and calculates link budgets for the mission duration in batch mode. On top of the link budget models inherited from DeSOL, SOLT incorporated several new models including analytic FOV, selection of optimal PPM order, variable seeing parameter, and data rate switching to maximize data volume.

SOLT allows the user to quickly evaluate a large number of link budgets for missions with duration spanning multiple years. This feature enables us to use performance trade studies to understand what types of optical communication infrastructure, e.g., ground terminals,

⁴ B. Moision, "Capacity of Poisson PPM Channel: Some Simple Approximations and Rules of Thumb," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, December 2008.

⁵ S. Piazzolla, "Finding the Data Rate and Slot Width for a Poisson PPM Channel, JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, August 2008.

⁶ S. Piazzolla, *Deep Space Optical Link (DeSOL) Software, Software Manual and Documentation* (internal document), Jet Propulsion Laboratory, Pasadena, California, 2008.

flight terminals, and geospatial locations of ground terminals, will best serve the anticipated mission concept of operations.

Figure 2 shows a snapshot of the SOLT user interface, indicating the array of parameters available for control of the link configurations.

JPL SOLT -- Strategic Optical Link Tool

Link Configuration

DOWNLINK MODULATION & LASER

SELECT PROFILE: USER DEFINED

MIN. SLOT TIME WIDTH (ns): 0.5

PPM MODULATION (M): MINIMUM 16, MAXIMUM 128

LASER WAVELENGTH (nm): 1550 nm, 1550

AVG. POWER (W): 4

SPECTRAL WIDTH (nm): 0.1

SPACECRAFT TRANSMITTER

TRANSMITTER: USER DEFINED

DIAMETER (cm): 22

BEAM WIDTH (urad): 8.3645

OPTICAL LOSS (dB): 3.09

POINTING ERROR (urad): 2.6

POINTING LOSS (dB): 1.1626

LINK MODE

DOWNLINK UPLINK

EPHEMERIS

SELECT TARGET BODY: USER DEFINED

SELECT LOCATION: GOLDSTONE, CA

CHANNEL

SITE ALTITUDE asl (km): 1

ATMOSPHERIC CHANNEL: CLEAR SKY

TURBULENCE: DESERT

ATMOSPHERIC LOSS (dB): 0.26712

SKY RADIANCE (W/cm²/um/sr): 0.00043297

FRIED PARAMETER (m): 0.23694

DETECTOR

SELECT DETECTOR: USER DEFINED

DETECTOR DE (%): 50

DETECTOR DARK RATE (Kcount/sec): 225

DETECTOR DIAMETER (mm): USER SPECIFIED 3

DETECTOR JITTER (ns): 0.1

NUMBER OF DETECTORS: 1

GROUND RECEIVER

SELECT RECEIVER: USER DEFINED

TELESCOPE DIAMETER (m): 11.8

FOCAL LENGTH (m): 124

FILTER BANDWIDTH (nm): 0.17

FILTER LOSS (dB): 0

OPTICAL LOSS (dB): 4.1

CLEANLINESS LEVEL: 1000

FOV SELECTION: ANALYTIC

FOV (urad): 13.154

RECEIVER

LINK MARGIN (dB): 3

ANALYSIS

ANALYSIS MODE: DATA RATE SWI...

LINK RESULTS

DATA RATE (Mbps): 30.6694

SLOT TIME WIDTH (ns): 0.95105

REQ'D PEAK POWER (W): 639.4904

Ks (PHE in Signal Slot): 1.7464

Kb (PHE in Noise Slot): 0.04403

DOT-like downlink to Gold Stone LBT 11.8-m telescope

CALCULATE Mission Plot

Figure 2. SOLT user interface.

For error-correcting code, SOLT assumes SCPPM (serial concatenation of convolutional code with an accumulator and PPM), attributing to its power efficiency for the noisy Poisson PPM channel. The code rate R_{ECC} is selected from the set $\{\frac{1}{2}, \frac{2}{3}\}$. The PPM order M is selected from the set $\{16, 32, 64, 128\}$. There are three type of detector profiles, i.e., nanowire, Geiger-mode avalanche photodiodes (GMAPDs), and indium-gallium arsenide-phosphite (InGaAsP) [15], that users may choose from. These detector prototypes were inherited from DeSOL detector models, each associated with characteristics such as photo detection efficiency, jitter, recovery time, and dark rate.

For a given spacecraft trajectory profile, SOLT calculates the supportable data rates as a function of time for a given link configuration. By changing the terminals and link characteristics, link budgets can be calculated and compared for different combinations of space and ground terminals, and for various weather and atmospheric conditions. This enables the user to quickly assess optical communication capabilities for long-term mission planning and to perform cost-performance trade studies of ground and space terminals.

A. Link Parameter Selection in SOLT

For each time instance of the mission profile, SOLT calculates the received signal and noise flux rates (λ_s, λ_b) , using the analytical FOV selection approach developed in [12]. This allows us to significantly simplify the optimization process of link parameter selection. We choose the triple, $\{R_{ECC}, M, T_s\}$, that maximizes the supportable data rate, $R_b = R_{ECC} \cdot \frac{\log_2 M}{M \cdot T_s}$, for the received signal and noise flux. Below shows the pseudocode for this optimization procedure in SOLT.

Algorithm 1 SOLT optimization procedure

```

1: for  $R_{ECC} \in \{\frac{1}{2}, \frac{2}{3}\}$  do
2:   for  $M \in \{16, 32, 64, 128\}$  do
3:      $T_s(R_{ECC}, M) \leftarrow \underset{\substack{T'_s: R_b(T'_s) \leq C_{ub}(\lambda_s, \lambda_b, T'_s, M) \\ T'_s \geq T_{s, \min}}}{\text{argmax}} \{R_b(T'_s)\}$ 
4:   end for
5: end for
6: Select  $\{R_{ECC}^*, M^*, T_s^*\}$  that maximizes  $R_b(M, R_{ECC}, T_s(M, R_{ECC}))$ 

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There are two approaches⁷; see also [10], for calculating the capacity upper bounds function $C_{ub}(\lambda_s, \lambda_b, T_s, M)$. We used the approach described by S. Piazzolla,⁸ which takes the minimum of three upper bounds, for calculation of C_{ub} . The maximum data rate as well as the optimal parameters are saved in the link budget. An inter-symbol guard time of length $M \cdot T_s / 4$ is used in the link budget calculation, leading to an effective data rate of $\frac{4}{5} R_b$.

B. Sample SOLT Link Budgets

SOLT link budgets can be presented in different ways depending on the purpose of the study. For example, Figure 3 shows the supportable data rates, as a function of time and range, for a Mars mission employing ground terminals with different aperture sizes of 11.8 m, 8 m, and 4 m. These plots often enable the user to see the first-order effects of link parameters, such as aperture size and distance, on achievable data rates.

VI. System Performance Under Near-Ideal Conditions

This section presents our calculations of the pass-averaged data rate and cumulative data volume for downlink and uplink, for a relevant period during each of the design reference missions. These calculations assumed clear sky and worst-case turbulence. These are nearly

⁷ S. Piazzolla, August 2008, op cit.

⁸ Ibid.

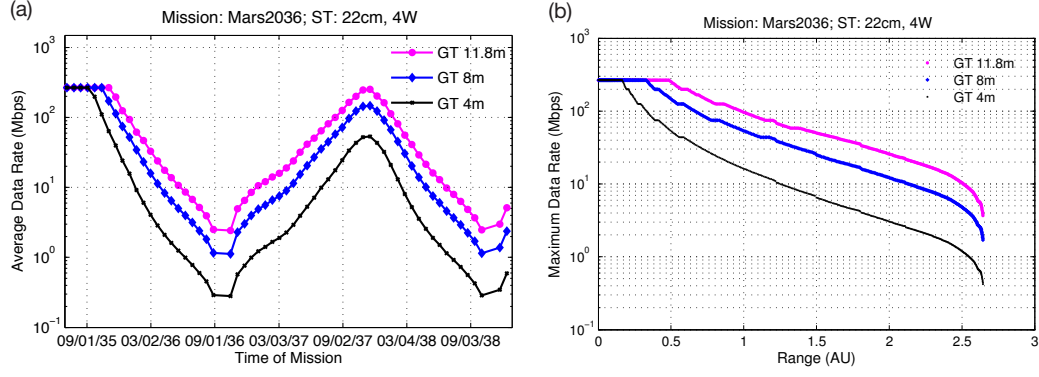


Figure 3. Sample data rate as functions of (a) time and (b) range for a Mars mission (Mars 2036, ST: 22 cm, 4 W).

ideal conditions, which do not take into account the probability of a cloud-free line of sight (CFLOS). As mentioned previously, the CFLOS probability varies by site, with typical values between 60 percent and 77 percent for good optical sites. The CFLOS probability does not affect the achievable data rate, but it does imply outages at irregular intervals that, over the long term and dependent on site, reduce the average achievable data rates and the cumulative data volume. The extent of this reduction depends on the operating concept for the link: for raw data delivery, the averages are reduced by the CFLOS probability. For automated repeat query (ARQ), the reduction is eliminated to first order, but limitations on the permissible offered load will reduce the averages slightly. The offered load limitations are discussed in [2].

The data rates are limited mainly by minimum slot width, code rates, and PPM orders. For example, [7], describing the DSOC terminal, identifies an uplink data rate limit at 292 kbps and a downlink data rate limit at 297 Mbps. However, it is unclear whether all potential terminals will have the same constraints. The possibility of mission-specific limits should be kept in mind when evaluating the calculated data rates.

A. Small Optical Terminal at Mars

The prototypes of missions for small optical terminal at Mars are either CubeSats at Mars or a terminal on the outside of a Mars lander. The goal is to provide a much higher data rate by relay to another optical communication asset orbiting Mars, or direct to Earth at a lower data rate but still higher compared to RF.

Figure 4 shows the average supportable data rates and cumulative data volume for a Mars mission downlink employing a small space terminal. The space terminal is assumed to have a 5-cm aperture and 1 W of average transmit power. Results are shown comparing ground receive terminals of 11.8 m, 8 m, and 4 m.

Figure 5 shows the average supportable data rates and cumulative data volume for a Mars mission uplink with a small space terminal. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW.

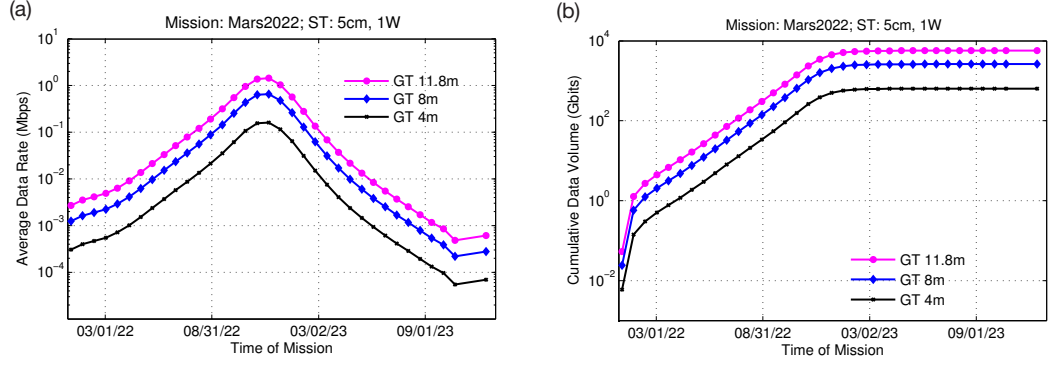


Figure 4. Average downlink data rate (a) and cumulative data volume (b) for a small optical terminal at Mars.

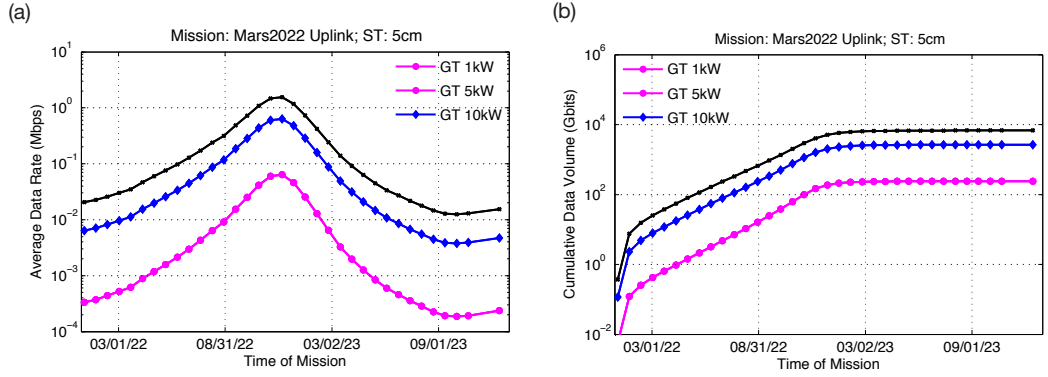


Figure 5. Average uplink data rate (a) and cumulative data volume (b) for a small optical terminal at Mars.

Figure 6 shows the average uplink signal irradiance for a small terminal at Mars. We assume the required minimum irradiance is 4 pW/m^2 , invariant to the aperture size [16]. This requirement can be met with ground transmit power of 5 kW and 12 kW.

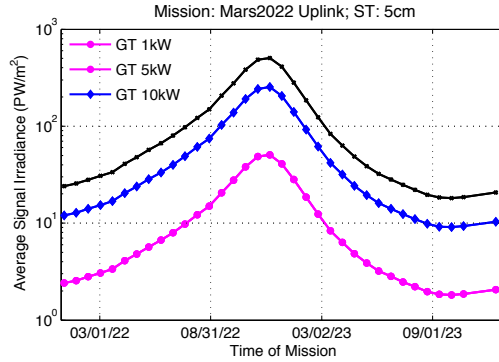


Figure 6. Average uplink irradiance for a small optical terminal at Mars.

B. Medium Optical Terminal at Mars

The prototype of missions for a medium optical terminal at Mars is an optical demonstration on a Mars orbiter sent for a scientific purpose. In this scenario, a Mars orbiter carries a DSOC terminal for a direct-to-Earth (DTE) link. The space terminal would have a 22-cm aperture and 4 W of transmit power.

Figure 7 shows the average supportable data rates and cumulative data volume for a Mars mission downlink employing a medium space terminal. Results are shown comparing ground receive terminals of 11.8 m, 8 m, and 4 m.

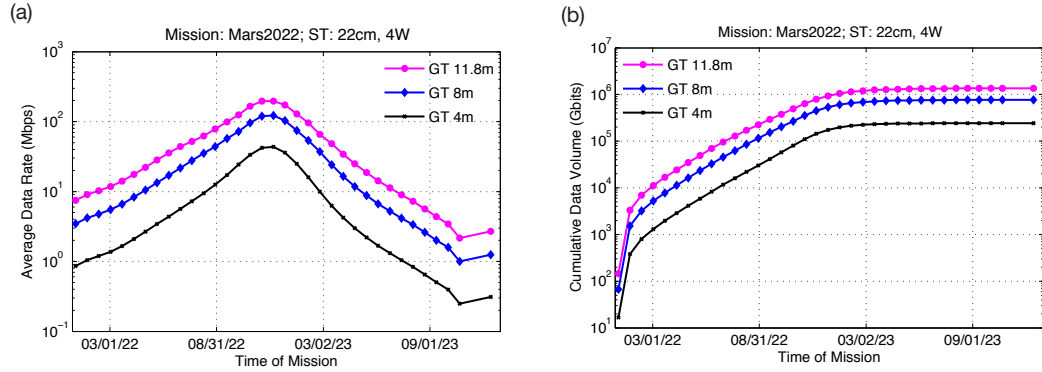


Figure 7. Average downlink data rate (a) and cumulative data volume (b) for a medium-sized optical terminal at Mars.

Figure 8 shows the average supportable data rates and cumulative data volume for a Mars mission uplink with a medium-sized space terminal. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW.

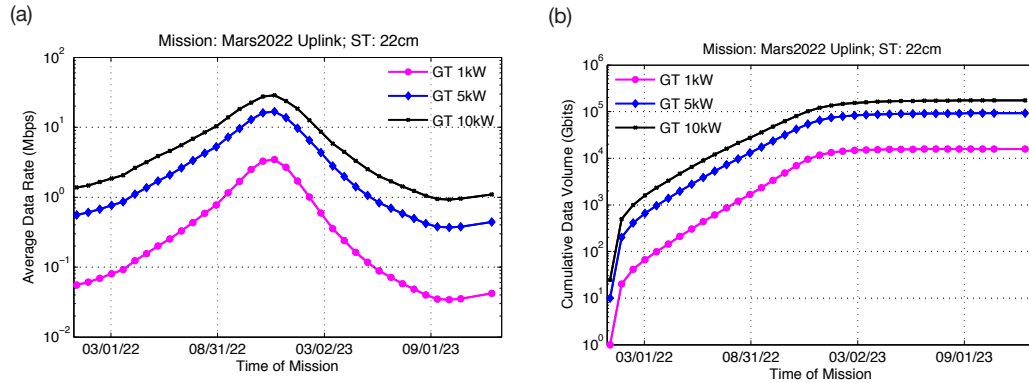


Figure 8. Average uplink data rate (a) and cumulative data volume (b) for a medium-sized optical terminal at Mars.

Figure 9 shows the average uplink signal irradiance for a medium-sized terminal at Mars. For a 22-cm aperture, the required minimum uplink irradiance is $\sim 4 \text{ pW/m}^2$. This requirement can be satisfied with ground transmit power of 5 kW and 10 kW. The link is weak at far range for the case when the ground terminal has transmit power of 1 kW.

C. Large Optical Terminal at Mars

The prototype of missions for a large terminal at Mars are potential crewed missions, either orbiting or landing on Mars, the latter being the more demanding case for an optical ground segment due to the number of assets involved and the associated high data rates. One

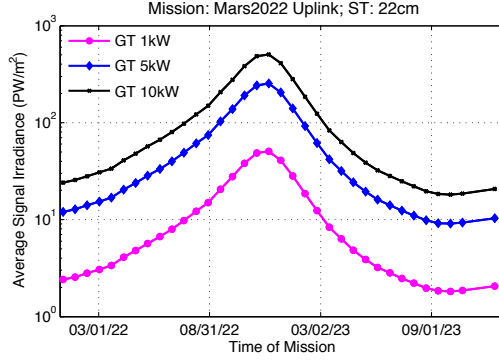


Figure 9. Average uplink irradiance for a medium-sized optical terminal at Mars.

estimate for the required data rate is believed to stem from legacy studies from the Constellation program circa 2007, i.e., 150 Mbps downlink and 25 Mbps uplink. The purpose of the high data rates is to carry high-definition television (HDTV), software uploads, and crew training materials. Another estimate based on International Space Station (ISS) experience is 250 Mbps (ISS current) to 600 Mbps (ISS future).

Figure 10 shows the average supportable data rates and cumulative data volume for a Mars mission downlink employing a large space terminal. Mars trajectory of 2035–2038 was used for this case. We assumed a 50-cm aperture and a 20-W transmitter for the space terminal. Results are produced and compared for ground receive terminals of 11.8 m, 8 m, and 4 m. Links operate in the bandwidth-limited regime at close range with data rate saturated at 267 Mbps.

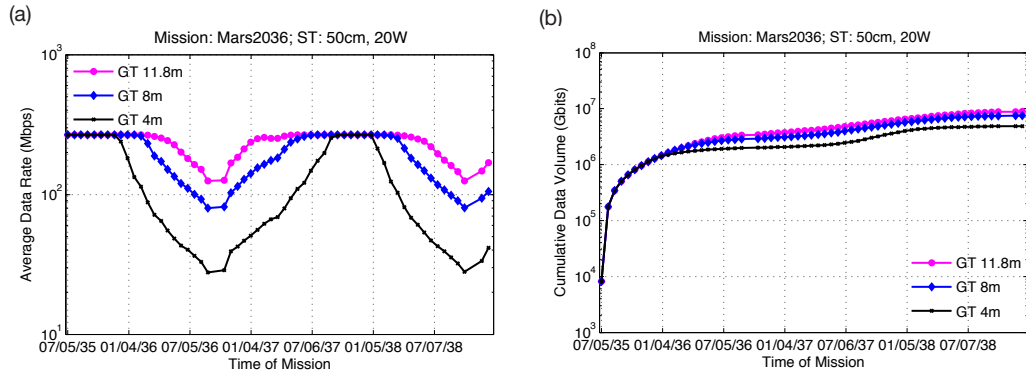


Figure 10. Average downlink data rate (a) and cumulative data volume (b) for a large optical terminal at Mars.

Figure 11 shows the average supportable data rates and cumulative data volume for a Mars mission uplink with a large space terminal. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW.

Figure 12 shows the average uplink signal irradiance for a large terminal. The required minimum signal irradiance can be satisfied with ground transmit power of 5 kW and 10 kW.

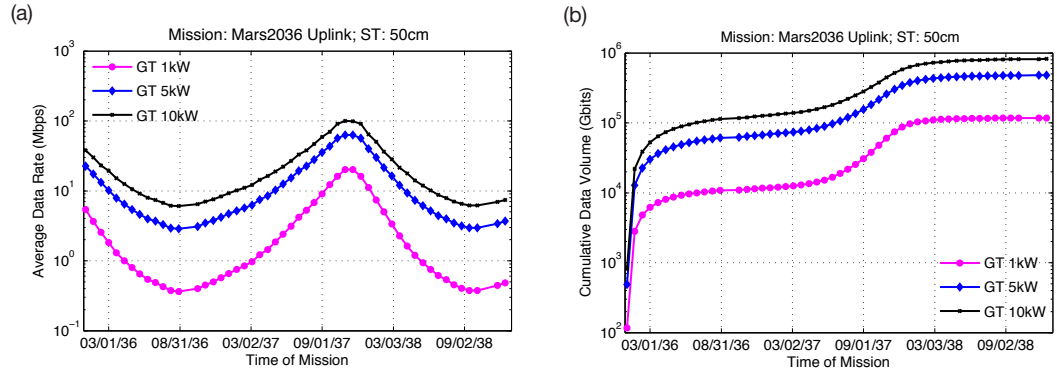


Figure 11. Average uplink data rate (a) and cumulative uplink data volume (b) for a large optical terminal at Mars.

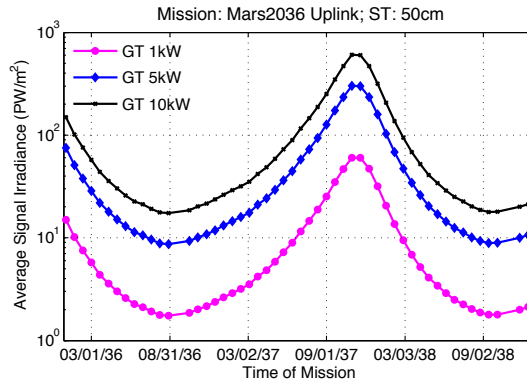


Figure 12. Average uplink irradiance for a large optical terminal at Mars.

D. Deep Space Observatory – Nighttime

The prototype mission for a deep-space observatory is the Wide-Field Infrared Survey Telescope (WFIRST). One version of the mission plans a trajectory to Earth–Sun L2 orbit launching in 2023. The spacecraft might first begin in a geosynchronous orbit, get checked out, and then transfer to SEL2. The required data rate was 150 Mbps at one time, but a recent request was received to investigate up to 262.5 Mbps.

We assume that an L2 mission can be placed in a halo orbit providing at least 5 deg of Sun–Earth–probe (SEP) angular offset. A medium-sized space terminal (22-cm aperture with 4 W of transmit power) was used in this link evaluation.

Figure 13 shows the average supportable data rates and cumulative data volume for an L2 mission downlink employing a medium-sized space terminal. We used SEP angles of 175 deg. This link operates in band-limited regime with data rate saturated at 267 Mbps.

Figure 14 shows the average supportable data rates and cumulative data volume for an SEL2 uplink with a medium-sized space terminal. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW. Again, links saturate for all three ground transmit terminals at a lower data rate than the downlink due to larger minimum slot widths of the space terminal. This represents a case where higher data rates can be achieved by lowering PPM order or using wavelength division multiplexing (WDM).

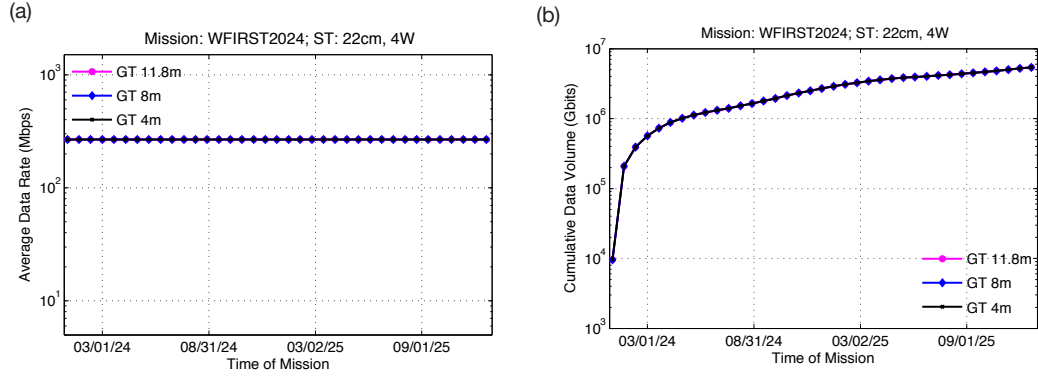


Figure 13. Average downlink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Nighttime.

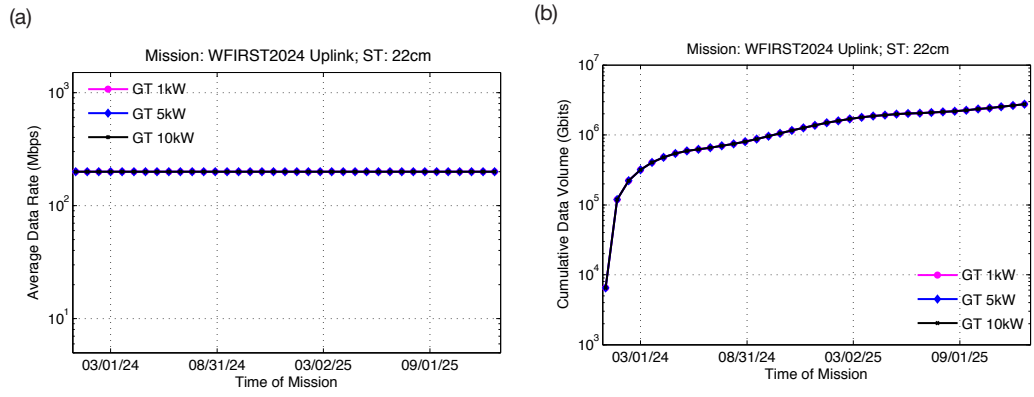


Figure 14. Average uplink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Nighttime.

Figure 15 shows the average uplink signal irradiance. The variation of signal irradiance is due to the variations of the range in a halo orbit.

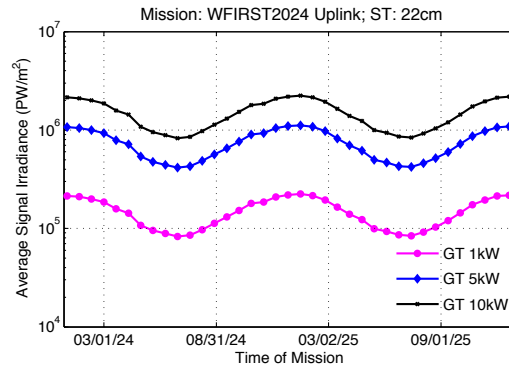


Figure 15. Average uplink irradiance for an L2 mission with medium-sized space terminal.

E. Deep Space Observatory – Dawn or Dusk

The prototype of missions for deep-space observatories in the dawn or dusk is the Whipple mission. The Whipple mission has an observatory spacecraft that would be placed in an Earth-trailing orbit (ETO) at about 0.4 AU. The spacecraft terminal is undefined, but the required data rate could be met with a terminal significantly smaller than the DSOC terminal (22 cm, 4 W) generally offered to Discovery missions. We used the small terminal (5 cm, 1 W) for link calculation of this reference mission.

Figure 16 shows the average supportable data rates and cumulative data volume for the downlink of an ETO mission with a small optical terminal.

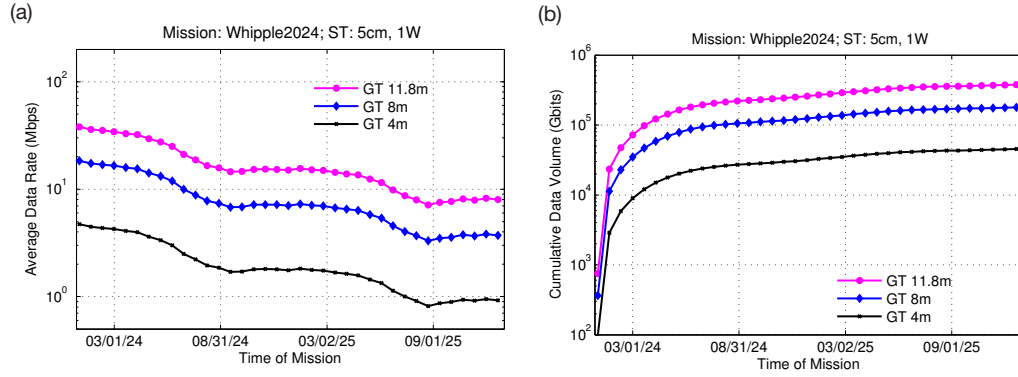


Figure 16. Average downlink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Dawn or Dusk.

Figure 17 shows the average supportable data rates and cumulative data volume for the Whipple mission uplink. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW.

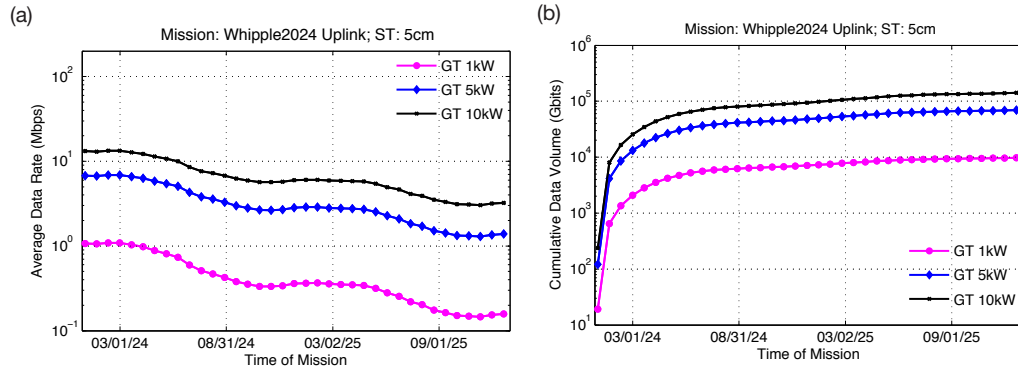


Figure 17. Average uplink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Dawn or Dusk.

Figure 18 shows the average uplink signal irradiance. The minimum signal irradiance required for a small space terminal can be satisfied in all three scenarios evaluated.

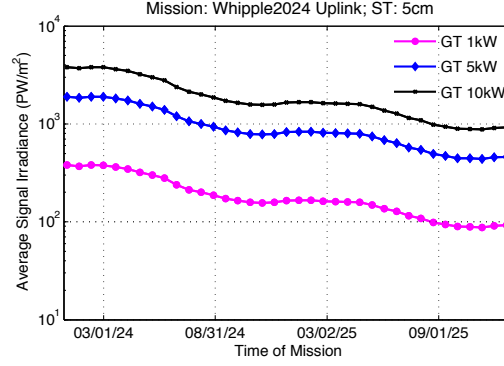


Figure 18. Average uplink irradiance for a Deep Space Observatory – Dawn or Dusk.

F. Deep Space Observatory – Daytime

The prototype of missions for deep space-observatories in the daytime direction from Earth is the NEOCam mission. This mission has a spacecraft that would be placed in an orbit at Sun–Earth Lagrange point 1, about 1 to 1.5 million km from Earth in the direction of the Sun, making it a daytime object as observed from Earth. The required data rate is about 30 Mbps (possibly up to 260 Mbps). The spacecraft optical terminal is unknown, but the required data rate can be met with a small terminal (5 cm, 1 W).

Figure 19 shows the average supportable data rates and cumulative data volume of a NEOCam mission downlink with a small optical terminal. Links saturated at 267 Mbps for all three ground receive terminals.

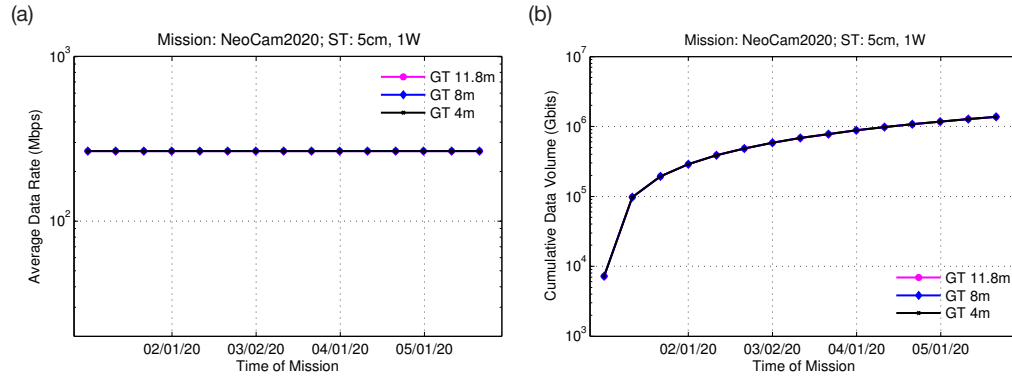


Figure 19. Average downlink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Daytime.

Figure 20 shows the average supportable data rates and cumulative data volume for a NEOCam mission uplink. Performances are compared for ground terminals with transmit power of 1 kW, 5 kW, and 10 kW. This design reference mission represents another case where lower PPM order, WDM, or a combination of two can be used to achieve higher data rates.

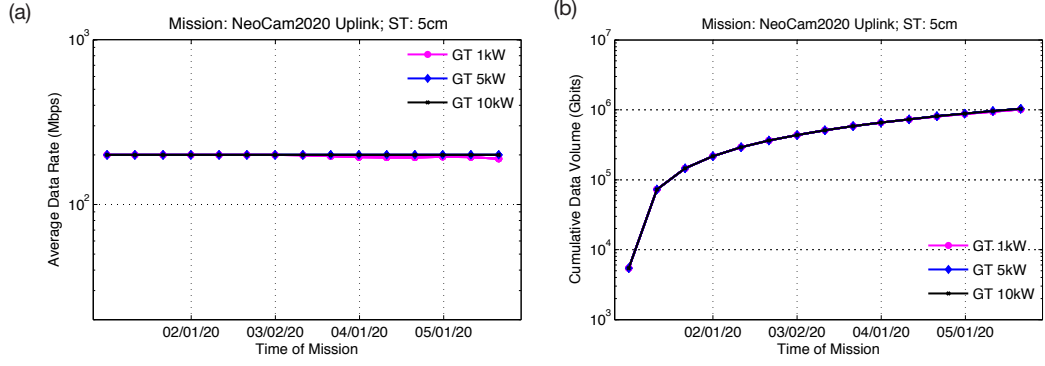


Figure 20. Average uplink data rate (a) and cumulative data volume (b) for a Deep Space Observatory – Daytime.

Figure 21 shows the average uplink signal irradiance. The minimum signal irradiance requirement can be met with all three transmit powers.

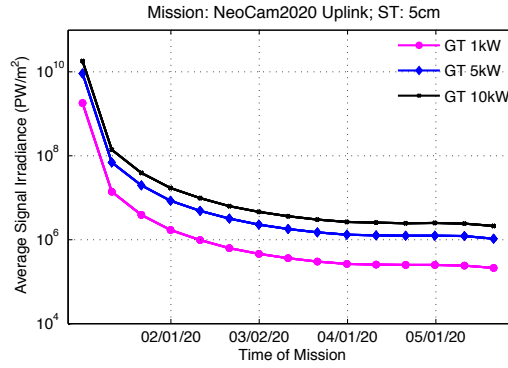


Figure 21. Average uplink irradiance for a Deep Space Observatory – Daytime.

G. Medium Optical Terminal at Jupiter Distance

The prototype of missions for a medium-sized optical terminal at Jupiter distance is the Trojan Tour and Rendezvous. In this mission, a spacecraft would travel to the vicinity of the Trojan cloud of asteroids, fly by multiple asteroids, rendezvous with one and possibly land on it. An average data rate of 12.5 kbps is required. The link budgets were calculated using a medium-sized space terminal (22 cm, 4 W).

Figure 22 shows the average downlink supportable data rates and cumulative data volume for a medium-sized optical terminal at Jupiter distance. Results are shown comparing ground receive terminals of 11.8 m, 8 m, and 4 m.

This is a low-data-rate, mass-power-volume driven mission where the size of the space terminal may be driven more by the difficulty of detecting an uplink beacon than by downlink data rate. It may require a larger spacecraft aperture or drive the ground segment to a more powerful uplink beacon.

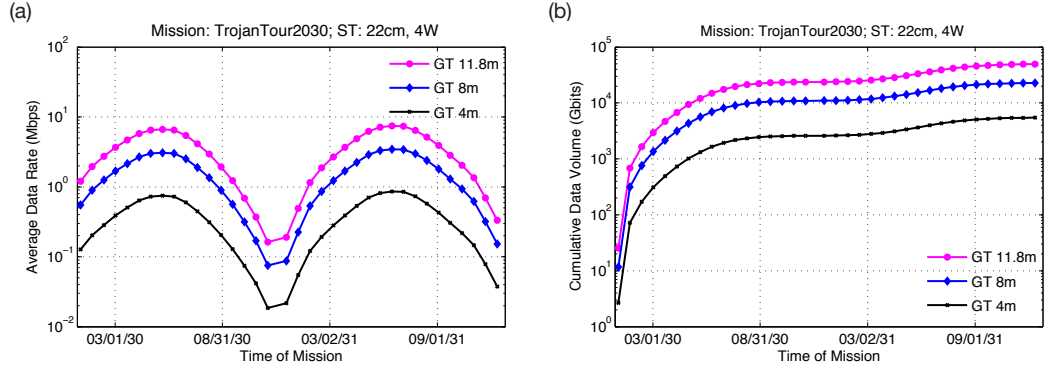


Figure 22. Average downlink data rate (a) and cumulative data volume (b) for a medium-sized optical terminal at Jupiter distance.

Figure 23 shows the average supportable data rates and cumulative data volume for the uplink. Figure 24 shows the average uplink signal irradiance.

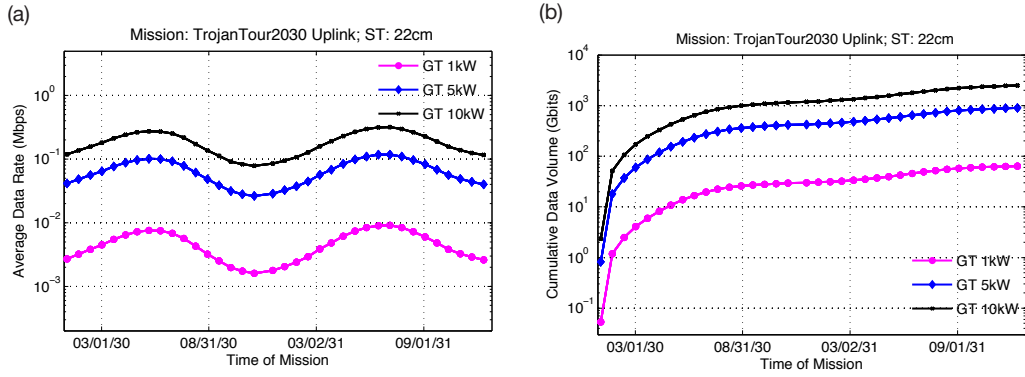


Figure 23. Average uplink data rate (a) and cumulative uplink data volume (b) for a medium-sized optical terminal at Jupiter distance.

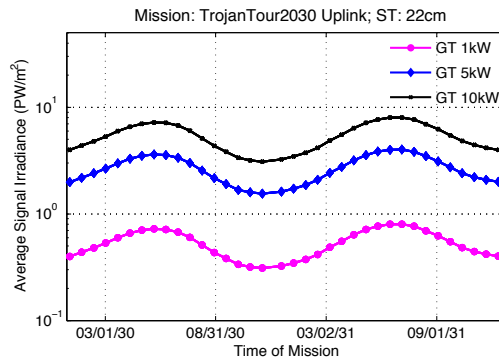


Figure 24. Average uplink irradiance for a medium-sized optical terminal at Jupiter distance.

H. Large Optical Terminal at Saturn

The prototype of missions for a large optical terminal at Saturn is the Saturn Atmospheric Probe. This mission would deploy a probe into Saturn's atmosphere to characterize its layers as well as noble gas abundances and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen. The large optical terminal is driven by the minimum signal irradiance required to acquire an uplink beacon.

Figure 25 shows the average supportable downlink data rates and cumulative data volume for a large optical terminal (50 cm, 20 W) at Saturn distance. Because it is of long duration and includes high-resolution cameras, the high data volume afforded by optical is beneficial [1].

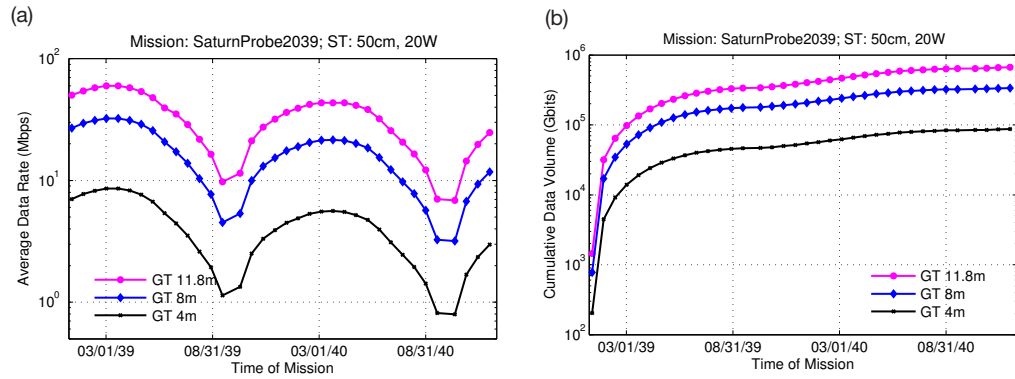


Figure 25. Average downlink data rate (a) and cumulative data volume (b) for a large optical terminal at Saturn distance.

Figure 26 shows the average uplink data rates and cumulative data volume.

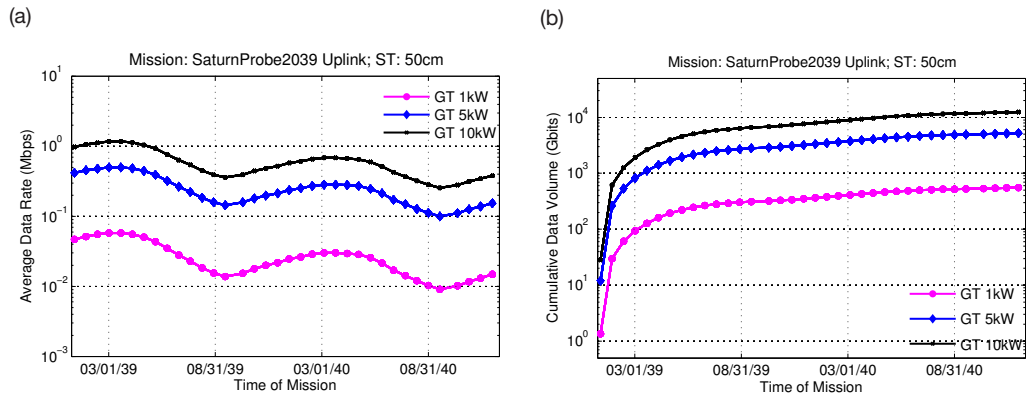


Figure 26. Average uplink data rate (a) and cumulative data volume (b) for a large optical terminal at Saturn distance.

Figure 27 shows the average uplink signal irradiance. This reference mission requires a large optical terminal and a more powerful uplink beacon (e.g., 50-cm aperture and 10-kW beacon).

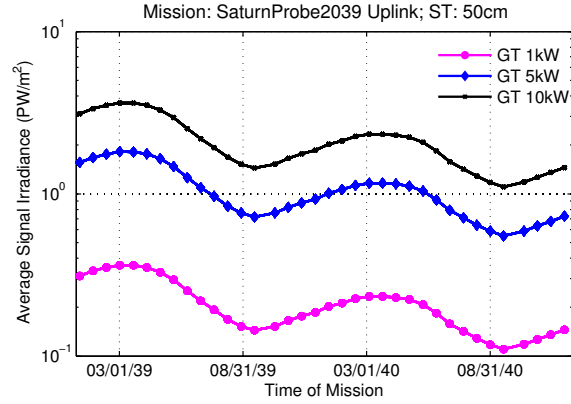


Figure 27. Average uplink irradiance for a large optical terminal at Saturn distance.

I. Large Optical Terminal at Jupiter

The prototype of missions for large optical terminals at Jupiter is the Europa Clipper mission. This mission will conduct detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life. The mission will place a highly capable, radiation-tolerant spacecraft in a long, looping orbit around Jupiter to perform repeated close flybys of Europa. The mission is of long duration and includes high-resolution cameras, for which the high data volume afforded by optical is beneficial.

Figure 28 shows the downlink average supportable data rates and cumulative data volume for a large optical terminal (50 cm, 20 W) at Jupiter.

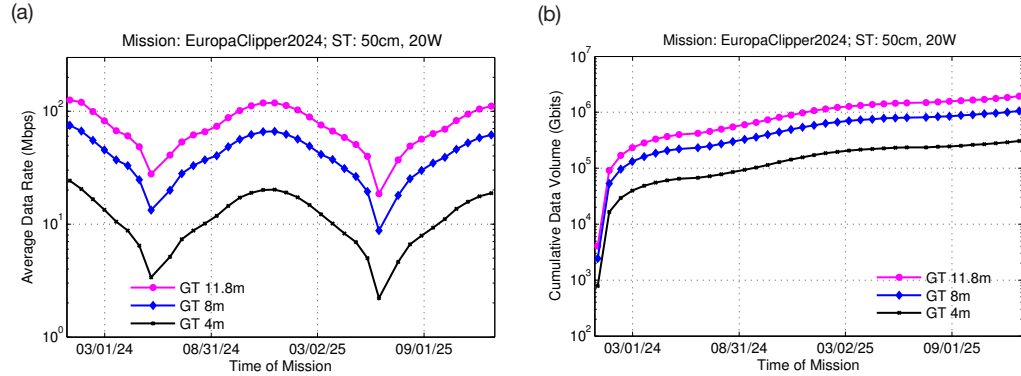


Figure 28. Average downlink data rate (a) and cumulative data volume (b) for a large optical terminal at Jupiter.

Figure 29 shows the uplink average data rates and cumulative data volume for a large terminal at Jupiter. Links are calculated for ground transmit powers of 1 kW, 5 kW, and 10 kW.

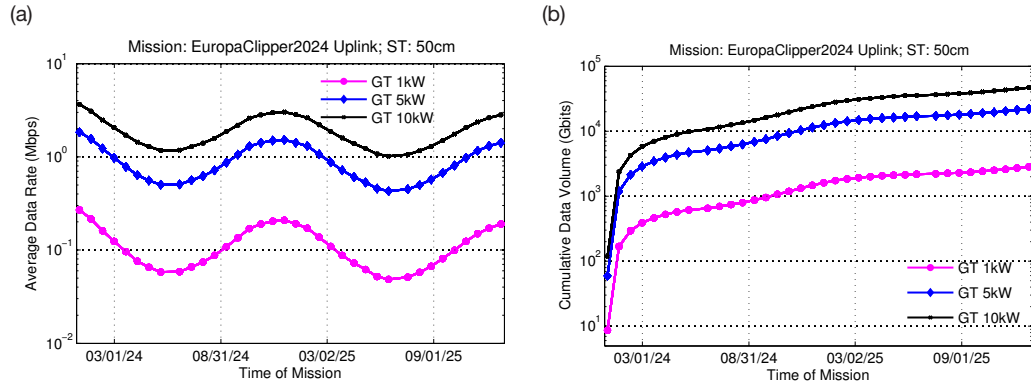


Figure 29. Average uplink data rate (a) and cumulative data volume (b) for a large optical terminal at Jupiter.

Figure 30 shows the average uplink signal irradiance.

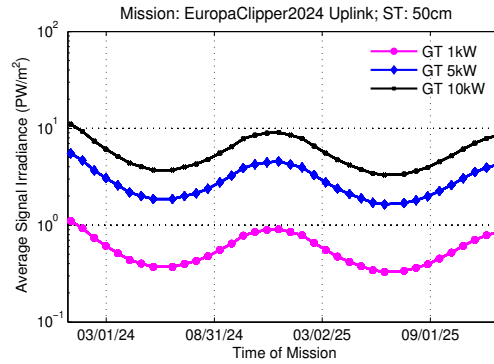


Figure 30. Average uplink irradiance for a large optical terminal at Jupiter distance.

J. Inner Planets

The prototype of missions for the inner planets is the Venus In Situ Explorer. This mission would characterize the chemical composition and dynamics of the atmosphere of Venus, and/or measure surface composition and rock textures. The mission potentially has a high data rate requirement needing optical communication. A DSOC medium-sized terminal (22 cm, 4 W) was used in the link budget calculation.

Figure 31 shows the downlink average supportable data rates and cumulative data volume for a medium optical terminal at Venus.

Figure 32 shows the average uplink data rates and cumulative data volume for a medium-sized terminal at Venus.

Figure 33 shows the average uplink signal irradiance. The minimum required irradiance can be met with all three cases of ground transmit power.

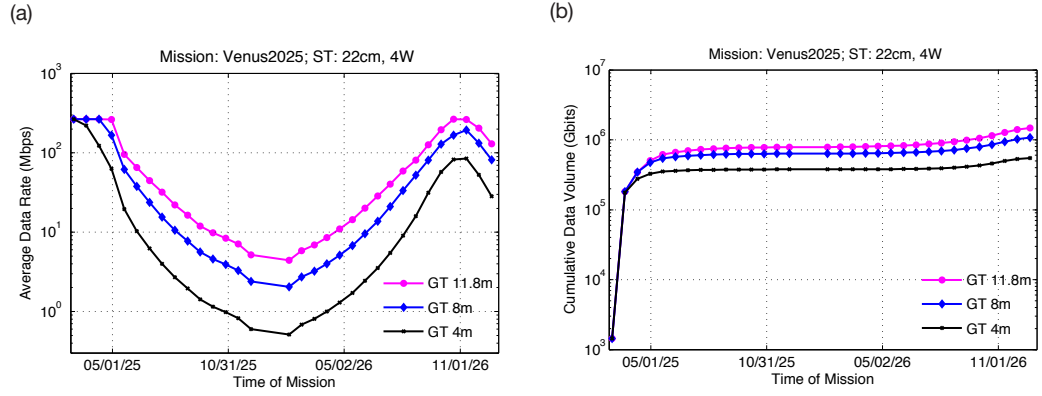


Figure 31. Average downlink data rate (a) and cumulative data volume (b) for a medium-sized optical terminal at Venus.

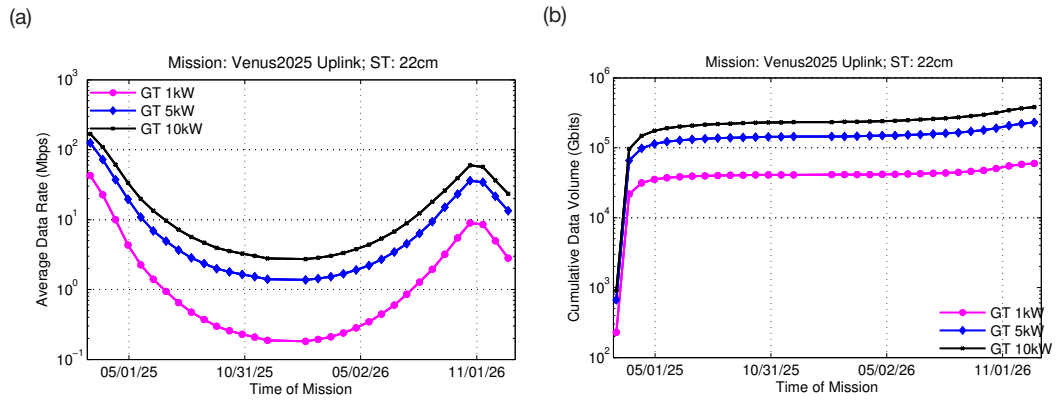


Figure 32. Average uplink data rate (a) and cumulative data volume (b) for a medium-sized optical terminal at Venus.

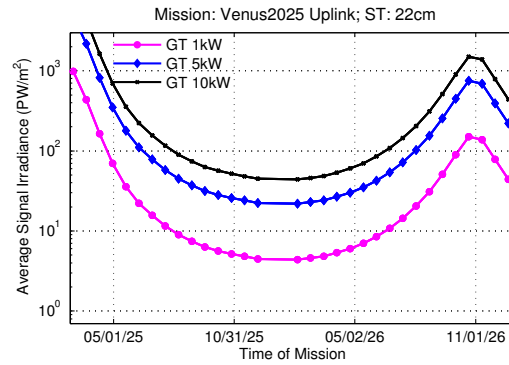


Figure 33. Average uplink irradiance for a medium-sized optical terminal at Venus.

K. Very Small Terminal at Lunar Distance

The prototype of missions for very small terminals at lunar distance is a CubeSat or a small landed instrument or relay that provides services in the context of a surrounding crewed mission. This type of mission also gives an idea of what might be possible with optical communication from geostationary or low-Earth-orbiting payloads, with appropriate scaling for distance. The best estimate for the required data rate for all the crewed deep-space missions, based on legacy studies from the Constellation program circa 2007, is 25 Mbps downlink and 6 Mbps uplink. The purpose of the high data rates is to carry HDTV, software uploads, and crew training materials.

Lunar missions are not a driver on the ground segment. However, a ground segment sized for interplanetary communication is so powerful that it opens up the possibility of new operations concepts using very small, ubiquitous laser comm terminals. Even if constrained for eye safety, very small space terminals with mW-level power and small apertures (mm to cm) may enable multi-Mbps data rates. For the link budgets in this section, we used a space terminal with 2-cm aperture and 2 mW of transmit power.

Figure 34 shows the average downlink data rates and cumulative data volume for a very small optical terminal at the Moon.

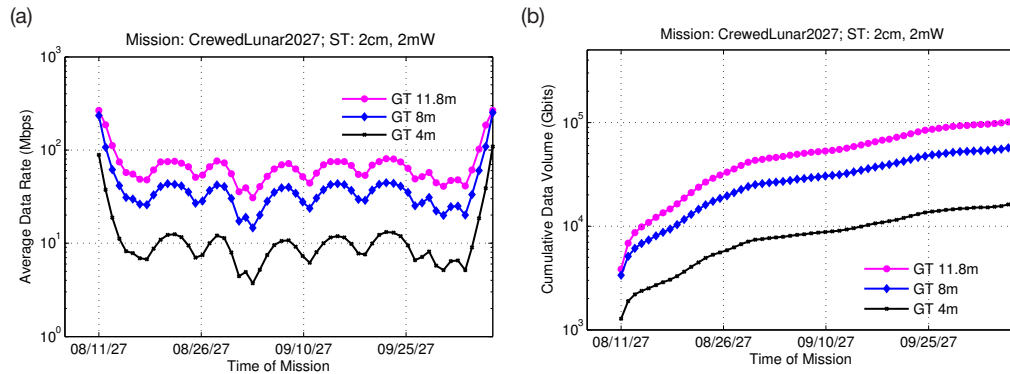


Figure 34. Average downlink data rate (a) and cumulative data volume (b) for a very small optical terminal at the Moon.

Figure 35 shows the average uplink data rates and cumulative data volume for a very small terminal at the Moon. Performances of ground terminals with transmit power of 10 W, 50 W, and 100 W are compared.

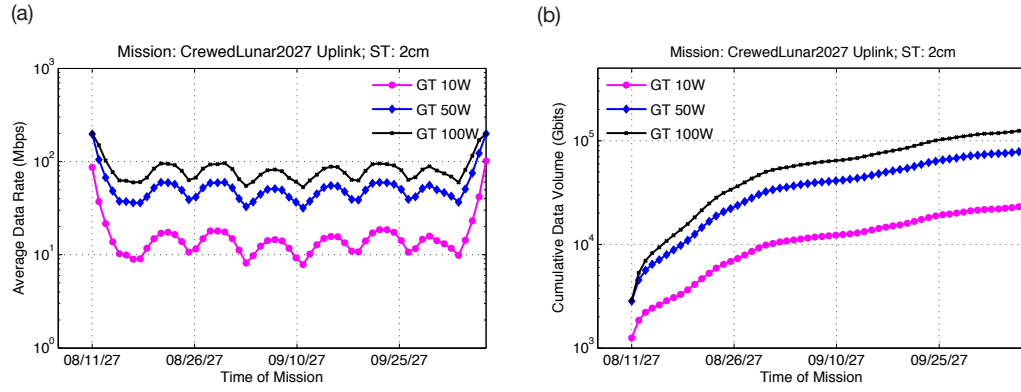


Figure 35. Average uplink data rate (a) and cumulative data volume (b) for a very small optical terminal at the Moon.

Figure 36 shows the average uplink signal irradiance.

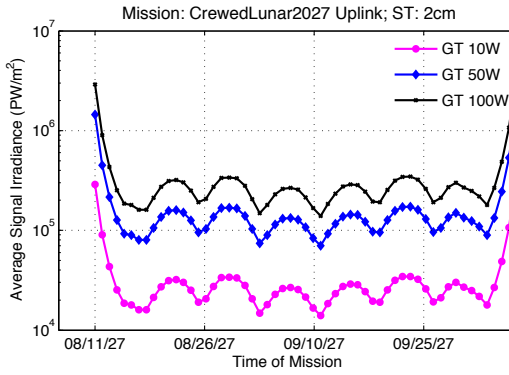


Figure 36. Average uplink irradiance for a very small optical terminal at the Moon.

L. Mars Trunk Line

The prototype of missions for a Mars trunk line is the Mars Aerostationary Relay. In this scenario, one or two satellites in orbit about Mars in aerostationary orbit would provide both communications and navigation capability for a number of potential user missions: science missions to the martian moons, relays for landers or sample return, and relays for crewed orbital or surface missions.

Figure 37 shows the average downlink data rates and cumulative data volume for a large optical terminal at Mars.

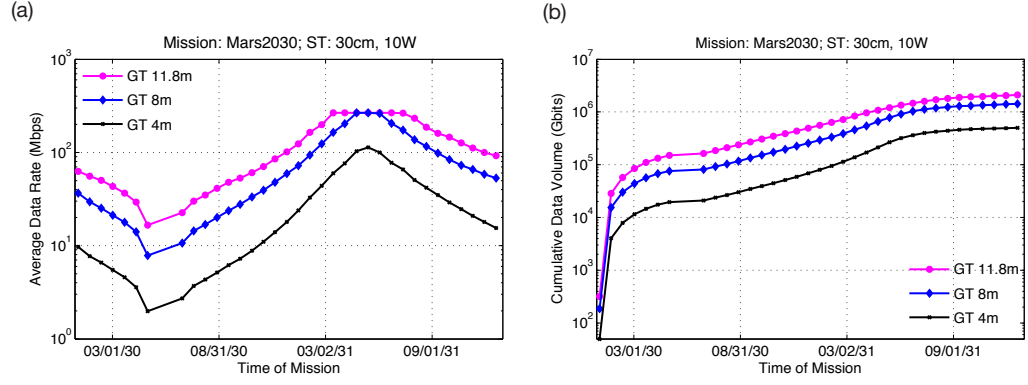


Figure 37. Average downlink data rate (a) and cumulative downlink data volume (b) for a large optical terminal at Mars.

Figure 38 shows the average uplink data rates and cumulative data volume for a large terminal at Mars. Performances of ground terminals with transmit power of 1 kW, 5 kW, and 10 kW are compared. In order to achieve ~250 Mbps data rate, a large ground terminal will be necessary.

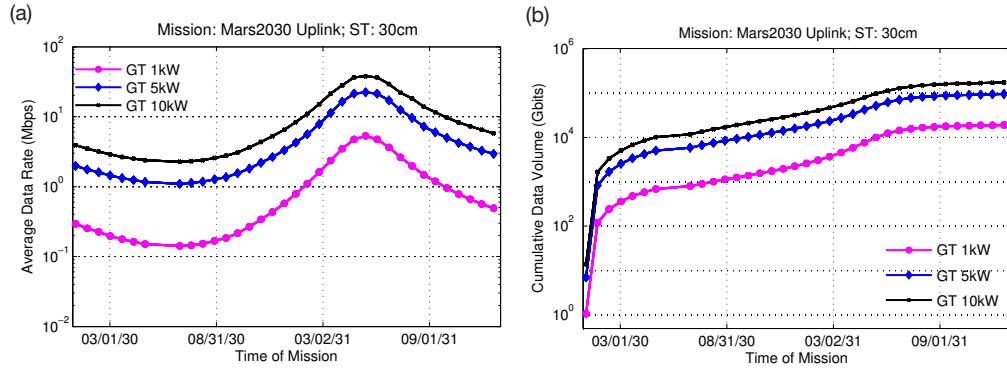


Figure 38. Average uplink data rate (a) and cumulative uplink data volume (b) for a large optical terminal at Mars.

Figure 39 shows the average uplink signal irradiance.

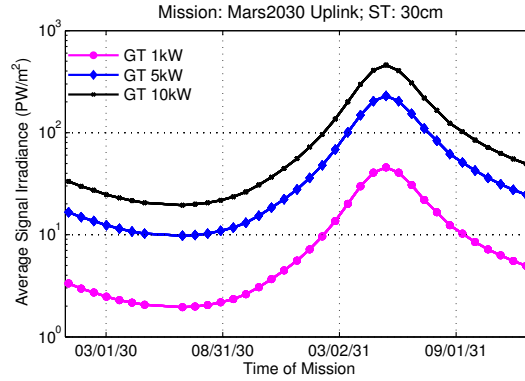


Figure 39. Average uplink irradiance for a large optical terminal at Mars.

VII. Summary and Conclusions

We examined the system performance of optical communications links using a single optical ground station and various space terminals, assuming three diameters of ground receive terminals: 4 m, 8 m, and 11.8 m (nominally 12 m). Ground transmit terminals with powers of 1 kW, 5 kW, and 10 kW were considered in most cases; for the one case of circumlunar communication, ground transmit powers of 10 W, 50 W, and 100 W were considered instead.

Combinations of ground receive terminals, ground transmit terminals, and spacecraft terminals were assessed for data rate and volume (both uplink and downlink), and for uplink irradiance needed to enable downlink pointing. The communication link parameters were optimized according to previously reported methods, embodied in the SOLT.

Basic optimistic assessments of raw physical link performance were made assuming clear weather conditions, with conservative assumptions about turbulence, the “desert daytime” case (zenith $r_0 = 5.5$ cm at 500 nm). The link results are compared with the anticipated requirements for the design reference missions.

Tables 4 and 5 summarize the downlink and uplink performance analysis of the design reference missions, respectively.

Figure 40 shows the link performances for multiple missions as a function of communication distance.

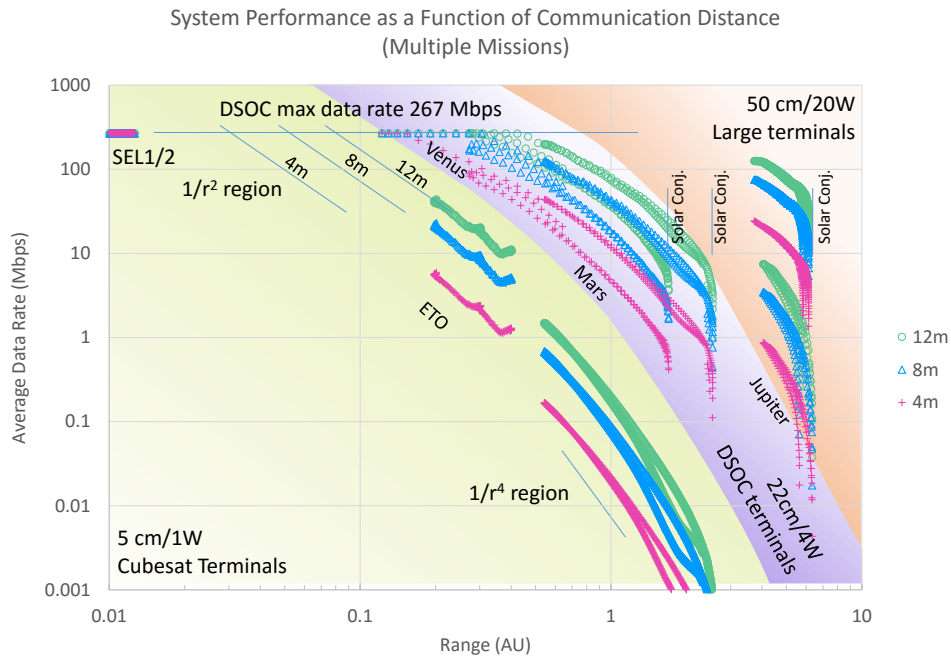


Figure 40. System performance for multiple missions as a function of communication distance.

Table 4. Summary of downlink performance analysis.*

Design Reference Mission Type	Downlink Data Rate Requirement	Satisfied by Ground Receive Terminal		
		11.8 m	8 m	4 m
Small Optical Terminal at Mars	~10 kbps DTE at 2.6 AU; ~128 kbps to 2 Mbps to relay orbiter	P	P	P
Medium Optical Terminal at Mars	> 5.2 Mbps	Y	Y	P
Large Optical Terminal at Mars	~150 Mbps–600 Mbps	Y	P	P
Deep Space Observatory–Nighttime	~150 Mbps–262.5 Mbps	Y	Y	Y
Deep Space Observatory–Dawn or Dusk	~2.5 Mbps	Y	Y	P
Deep Space Observatory–Daytime	~30 Mbps; possibly up to 260 Mbps	Y	Y	Y
Medium Optical Terminal at Jupiter Distance	~12.5–30 kbps	Y	Y	P
Large Optical Terminal at Saturn	~1.6 kbps relay [1 Mbps]	Y [Y]	Y [Y]	Y [P]
Large Optical Terminal at Jupiter	~134 kbps	Y	Y	Y
Inner Planets	~25 kbps to ~14.5 Mbps relay	P	P	P
Very Small Terminal at Lunar Distance	~25 Mbps; early desire for ~150 Mbps	Y	P	N
Mars Trunk Line	~250 Mbps	P	P	N

* Y = requirement satisfied; N = requirement not satisfied; P = requirement satisfied part of the time.

Table 5. Summary of performance analysis.†

Design Reference Mission Type	Uplink Data Rate Requirement	Satisfied by Ground Transmit Terminal			Uplink Beacon Irradiance Requirement, $\mu\text{W}/\text{m}^2$	Satisfied by Ground Transmit Terminal		
		10 kW	5 kW	1 kW		10 kW	5 kW	1 kW
Small Optical Terminal at Mars	[1 kbps*]	Y	Y	P	4	Y	Y	P
Medium Optical Terminal at Mars	[100 kbps*]	Y	Y	P	4	Y	Y	P
Large Optical Terminal at Mars	~25 Mbps	P	P	N	4	Y	Y	P
Deep Space Observatory — Nighttime	[100 Mbps*]	Y	Y	Y	4	Y	Y	Y
Deep Space Observatory — Dawn or Dusk	[1 Mbps*]	Y	Y	P	4	Y	Y	Y
Deep Space Observatory — Daytime	[100 Mbps*]	Y	Y	Y	4	Y	Y	Y
Medium Optical Terminal at Jupiter Distance	[1 kbps*]	Y	Y	Y	4	P	N	N
Large Optical Terminal at Saturn	[10 kbps*]	Y	Y	Y	4	N	N	N
Large Optical Terminal at Jupiter	[10 kbps*]	Y	Y	Y	4	P	P	N
Inner Planets	[100 kbps*]	Y	Y	Y	4	Y	Y	Y
Very Small Terminal at Lunar Distance	6 Mbps	Y	Y	Y	4	Y	Y	Y
Mars Trunk Line	[100 kbps*]	Y	Y	Y	4	Y	Y	Y

† Y = requirement satisfied; N = requirement not satisfied; P = requirement satisfied part of the time.

* Provisional value in absence of customer statement

Table 6 shows the approximate maximum communication distance for an optical link to close at maximum data rates (DSOC planned upper range) using different space terminals.

Table 6. Approximate maximum communication distance for optical link to close at maximum data rates (DSOC planned upper range).*

Terminal Type	Rate	Ground Receive Terminal		
		4 m	8 m	11.8 m
50 cm / 20 W	267 Mbps	0.75 AU	1.5 AU	2.2 AU
22 cm / 4 W	267 Mbps	0.16 AU	0.32 AU	0.48 AU
5 cm / 1 W	267 Mbps	0.018 AU	0.035 AU	0.052 AU

* Values are calculated for SEP = 180 deg, zenith angle 45 deg, turbulence $r_0 = 5.5$ cm at 500 nm.

The downlink data rates desired for all the DRMs, except the crewed missions, can be supplied at closest approach to Earth within the level of technology planned for the DSOC terminal, and with Earth receive terminals in the 4- to 12-m aperture range. However, the smaller apertures provide substantially less cumulative data volume over a mission, and a substantially smaller distance at which a given data rate can be achieved. The smaller apertures therefore dilute a customer's return on their investment in an optical terminal. The range at which a DSOC terminal can achieve its full data rate of 267 Mbps is approximately 0.48, 0.32, or 0.16 AU for 12-m, 8-m, or 4-m ground receive terminals.

Within our assumptions, downlink data rates from a 50-cm, 20-W large optical terminal at Mars to a 12-m ground aperture are a factor of 2 or 3 lower than the 600 Mbps at 2.5 AU upper range desired by crewed customers in the late 2030s, but above their lower range of desire for 150 Mbps at 2.5 AU. Data rates to 8-m and 4-m apertures would fall below the requirement at maximum range. The primary limiting factor in our analysis was not Earth- or space-based aperture, rather, it was detector speed on Earth and a self-imposed requirement to maintain photon efficiency that set the upper limit on data rate. If the customer desire for 600-Mbps data rates is to be satisfied, faster detectors, larger arrays of detectors, or other means such as lowering the PPM order (and concomitantly link efficiency and using wavelength division multiplexing [WDM]), or combinations of all of these, could be pursued. We understand that sufficient improvement in detector speed can probably be achieved with a few million dollars of technology investment, and we confirmed in a point calculation that lower PPM order and a 12-m ground aperture comes closer to satisfying the desire. If this primary limiting factor is overcome, the next limit is spacecraft laser power. This could be addressed by continued research on 20-W and 100-W spacecraft lasers capable of PPM.

Achievable uplink data rates in general are severely constrained by the modulation bandwidth and peak-to-average power ratio of the existing uplink lasers to 2 kbps, even though enough uplink power is available to achieve multimegabit performance were faster lasers and spacecraft electronics available. With research activities already in progress for faster high-power lasers, it is conceivable that data rates could be drastically increased, to the point where the data rate would only be constrained by the power available. However, the technology maturation of faster high-power lasers will need continued attention. When

this limit is overcome, the next limit is flight detector readout electronics and processing, which presently limit uplink data rate to less than about 1 Mbps.

With improved uplink lasers and flight detector readout electronics and processing, the power-limited uplink data rates from Earth ground stations to large optical terminals at Mars are still a factor or two to ten lower than the 25 Mbps minimum desired by crewed customers, even with the maximum-power (10-kW) transmitter we considered.

Constraints on uplink irradiance needed for the beacon mode of downlink pointing exclude the lower-power (1 kW or less) Earth transmitters we considered, but the larger transmitters (5 kW and 10 kW) satisfy the constraint in many cases. Also, the uplink irradiance requirement is not met at Saturn by the largest transmitter we considered (10 kW). If the downlink is constrained to use the full aperture, this shortfall is not directly helped by larger spacecraft aperture because of its tighter pointing requirements. However, a relaxation of this constraint to allow increased receive aperture and subaperture transmission would broaden the downlink beam, reduce pointing requirements, and reduce the required uplink power.

Small optical terminals for CubeSats or other applications are an emerging need, but as yet are a subject of research as to their capabilities. Nonetheless, we explored small terminals in the spirit of a “what if” study, assuming the space terminal to have either a 5-cm aperture and 1 watt of transmitter power, or a 2-cm aperture and 2 mW of transmitter power. We assumed diffraction-limited pointing, peak/average power ratio of the lasers greater than 128, and PPM. These characteristics are not currently achievable within mass, power, and volume constraints consistent with 5-cm or 2-cm apertures, but are used as placeholders for a “what if” study. With this in mind, we found that the hypothetical 5-cm terminal might deliver raw bit rates of 267 Mbps at 0.052 AU, 0.035 AU, or 0.018 AU to 12-m, 8-m, or 4-m ground apertures under clear nighttime conditions. We found that such a terminal might provide more than 267 Mbps from Earth–Sun Lagrange point 1 for any of the ground apertures considered, and 1 Mbps from Mars at closest approach to a 12-m ground aperture. For the hypothetical 2-cm, 2-mW terminal at lunar distance, we found that a data rate of 20 Mbps could be supported to a 12-m ground aperture. These data rates should be regarded as very approximate descriptions from a “what if” study and should only be used for broad considerations that would remain applicable when rescaled to reflect the true architecture of any particular small terminal.

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